3 SOIL, THE SUSTAINER

Soil, which is called pedosphere, can be envisioned as a chemical reservoir created at the earth's surface by the interaction of four great chemical reservoirs and powered by solar energy (Figure 3.1). Soil has sustained plants and animals since life began on the planet Earth. Soil is made up of all three physical forms of a matter, namely, solid, liquid, and gas. On a volume basis nearly half the soil is solid, while the other half is made up of soil, water and air. The amount of air in a soil depends upon its water content; at optimum water content for the growth of most upland plants, water and air may each make up about 30 and 20% of the soil volume, respectively (Figure 3.2*A*). Tillage practices can influence the proportion of water and gases in surface soil. In rice paddies, however, where water floods the soil, the only oxygen present is that dissolved in soil water (Figure 3.2*B*).

As regards the solid phase, 95% or more of it is mineral (inorganic) in nature, while the remaining 5% or less is organic in nature. However, in temperate and cooler regions of the world soil organic matter may be 5 to 10% or even more of the solid phase, while in warm tropical and subtropical soils organic matter content could be much less than 5%. Thus the proportion of mineral and organic matter differs considerably from soil to soil, depending particularly on the climate of the region.

3.1. SOIL ORGANIC MATTER

Soil organic matter originates from plant and animal residues, which are generally present in various stages of decomposition, namely, from fresh additions to well-decayed soil humus. Although a detailed discussion on soil organic matter is provided later (Chapter 5), it needs to be mentioned that soil organic matter controls several soil physical and chemical properties. Soil organic matter increases the water-holding capacity of soils and is a source of several essential plant nutrients, especially N, S, and P. It is also a source of energy for soil microorganisms. Some general properties of soil organic matter and associated effects on soil properties are given in Table 3.1. Were it not for soil organic matter, there would hardly be life in soil. Management of crop

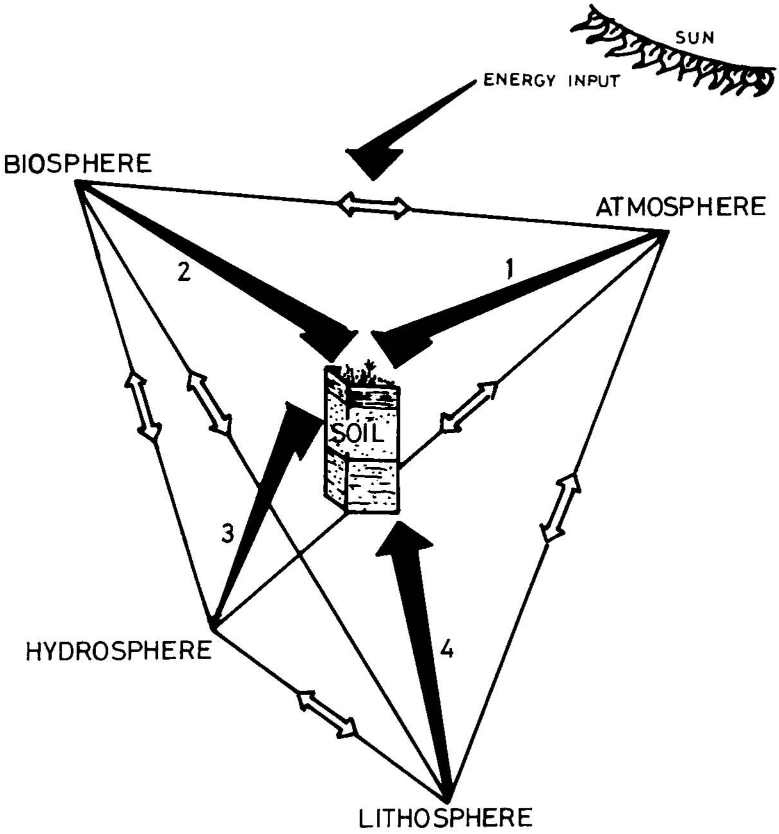


Figure 3.1. The interactions of the four great chemical reservoirs at the earth's surface, which, powered by solar energy, produce soil. (From Chesworth, 1991. Micronutrients in Agriculture, J.J. Mortvedt, F.R. Cox, L.M. Shumah, and R.M. Welch, Eds. With permission of Soil Science Society of America, Madison, WI.)

residues and returning farm wastes to cultivated fields form essential components of soil fertility management for sustainable agriculture.

3.2. SOIL WATER

Sustainability of the agriculture of a country or region depends much on how soil water is managed. Associated major problems require the management of both surface and underground water. Water infiltrates the pores between soil particles and is held with varying degrees of tenacity. Soil water can be measured directly by weight loss on drying, or by using a soil water tensiometer, gypsum or nylon blocks, or a neutron or time-domain reflectance (TDR) probe. The tenacity or soil tension with which water is held by soil particles increases as the soil water content decreases. Water tension in soil at

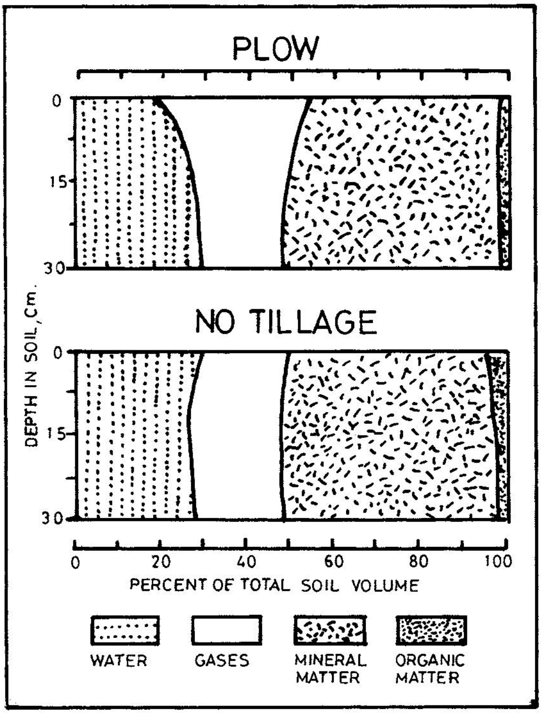


Figure 3.2A. Volume composition of soil when plant growth is in good condition. Tillage increased oxygen concentration in surface (7–8 cm) soil layer. (From Doran, 1982. Crops and Soils Magazine 34:10–12. With permission of ASA.)

any moment controls movement of soil water in soil and its use by plants. When tension is between 0.01 and 0.03 *M* Pa*, water moves to lower layers due to gravitational pull. Also when soil water tension is 1.5 *M* Pa or above, the adhesive force is so strong that plant roots can hardly extract water from soil. At approximately this water tension, most plants permanently wilt and stop growing. Soil water between about 0.01 and 1.5 *M* Pa is considered available to plants.

In addition to its essentiality for life *per se* soil water also serves as a carrier of plant nutrients. All plant nutrients are absorbable by plant roots after these come in solution. Thus the management of soil water forms an integral part of soil fertility management.

3.3. SOIL AIR

The content and composition of soil air is determined by soil-water relationships. Soil air differs from that in the atmosphere in several aspects. Soil

* The earlier unit used for soil moisture tension was atmospheres: 1 atmosphere = 0.1 *M* Pa.

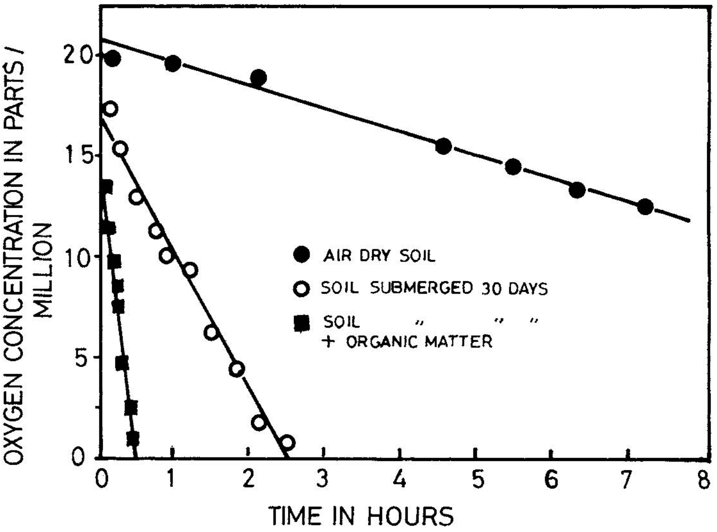


Figure 3.2B. The oxygen concentration of Corwley silt loam after saturation with oxygen as affected by submerging the soil and by the addition of organic matter. (From Patrick and Sturgis, 1955. Soil Sci. Soc. Am. Proc. 19:59–62. With permission of Soil Science Society of America, Madison, WI.)

air is much more moist and contains several hundredfold greater carbon dioxide concentration than the atmosphere. As a result oxygen content in soil air decreases considerably and may be 10 to 12% or less as compared with 21% for the normal atmosphere. Air moves through the soil pores primarily by diffusion, so diffusion rates are many times greater in air-filled than water-filled pores.

Because of the presence of pores between soil particles, the soils have two kinds of densities, namely, bulk density and true or particle density. Bulk density is defined as the mass (weight) per unit volume of soil; this volume includes both solids and pores. True or particle density of soil, on the other hand, is the mass (weight) per unit volume of soil particles. The relationship between bulk density (BD), particle density (PD), and pore space in soil is expressed below:

$$\text{Pore space (\%)} = 100\,(1 - \text{BD/PD}) \tag{1}$$

In most mineral soils particle density is normally about 2.65 Mg m^{-3}, nearly twice that of bulk density. Bulk density in soils generally varies from 1.0 to 1.8 Mg m^{-3}. Bulk density in very compact soils may be as high as 2.0 Mg m^{-3}. Soils with lower bulk density are easy to cultivate and manage. Addition of farmyard manure and crop residues over years can lower the bulk density.

Table 3.1 General Properties of Soil Organic Matter and Associated Effects on Soil Properties

Property	Remarks	Effect on Soil
Color	The typical dark color of many soils is caused by organic matter	May facilitate warming
Water retention	Organic matter can hold up to 20 times its weight in water	Helps prevent drying and shrinking. May significantly improve the water-retaining properties of sandy soils
Combination with clay minerals	Cements soil particles into structural units called aggregates	Permits exchange of gases, stabilizes structure, increases permeability
Chelation	Forms stable complexes with Cu^{2+}, Mn^{2+}, Zn^{2+}, and other polyvalent cations	May enhance the availability of micronutrients to higher plants
Solubility in water	Insolubility of organic matter results from its association with clay. Also, salts of divalent and trivalent cations with organic matter are insoluble. Isolated organic matter is partly soluble in water	Little organic matter is lost by leaching
Buffer action	Organic matter exhibits buffering in slightly acid, neutral, and alkaline ranges	Helps to maintain a uniform reaction in the soil
Cation exchange	Total acidities of isolated fractions of humus range from 300 to 1400 cmol kg^{-1}	May increase the cation exchange capacity (CEC) of soil. From 20 to 70% of the CEC of many soils (e.g., Mollisols) is caused by organic matter
Mineralization	Decomposition of organic matter yields CO_2, NH_4^+, NO_3^-, PO_4^{3-}, and SO_4^{2-}	A source of nutrient elements available for plant growth
Combines with organic molecules	Affects bioactivity, persistence and biodegradability of pesticides	Modifies application rate of pesticides for effective control

From Stevenson. 1982. *Humus Chemistry*, p. 18. With permission of John Wiley & Sons, New York.

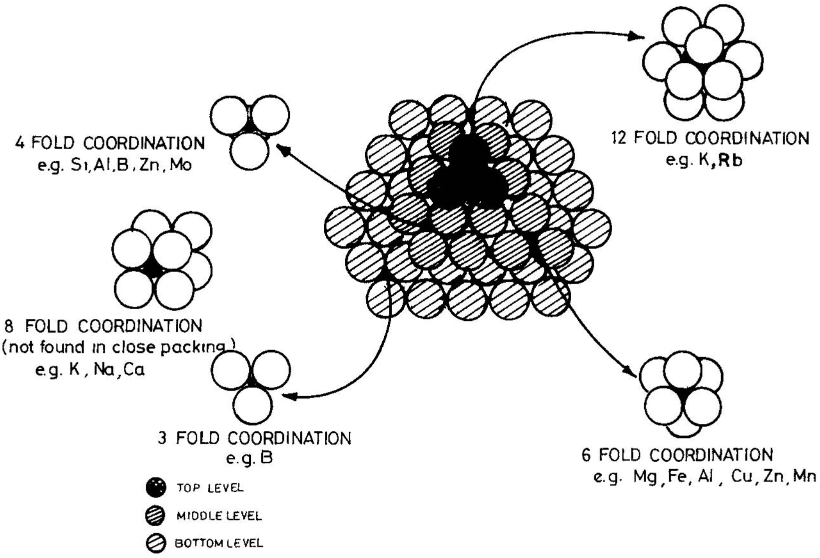


Figure 3.3. Close packing of oxygen anions as a model for the crust of the earth, showing typical coordination structures for the plant nutrients and other elements. (From Chesworth. 1991. Micronutrients in Agriculture, J.J. Mortvedt, F.R. Cox, L.M. Shumah, and R.M. Welch, Eds. With permission of Soil Science Society of America, Madison, WI.)

3.4. SOIL MINERAL MATTER

Oxygen and Si make up most of the soil mineral matter. Ninety percent of the volume of soil particles is O; the O atoms are hexagonally packed (each oxygen atom touches six of its neighbors). Other elements such as Si, Al, and Fe fill the voids left in oxygen packing. The position of these ions depends upon their ionic radii and radius ratio of the concerned ion and oxygen, which also determines their coordination number (number of oxygen ions shared) (Figure 3.3) (Table 3.2).

3.4.1. Soil Texture

Soil mineral particles can vary in size from coarse (over 2 mm) to very fine (less than 2 μm). Depending upon their size, soil particles are divided into gravel, sand, silt, and clay, which are known as soil separates. Regarding particle size for different soil separates, there is considerable variation in the limits set for sand and silt particles by different classifications. Limits set by the International Society of Soil Science and the U. S. Department of Agriculture are given in Table 3.3.

Table 3.2 Most Common Elements and Their Volume in Particulate Matter of Earth's Crust, Their Ionic Radii, Coordination Number, and Frequently Encountered Configuration

Element	Volume %	Ionic radii (nm)[a]	Coordination number	Configuration
O^{2-}	89.84	0.140	—	
Si^{4+}	2.37	0.039	4	Tetrahedral
Al^{3+}	1.24	0.051	4, 6	Tetrahedral Octahedral
Fe^{3+}	0.79	0.074	6	Octahedral
Mg^{2+}	0.60	0.066	6	Octahedral
Ca^{2+}	1.39	0.099	8	
Na^{+}	1.84	0.097	8	Cubic
K^{+}	1.84	0.133	8–12	
Mn^{4+}	0.01	0.060	6	
Ti^{4+}	0.08	0.068	6	

[a]1 nm = 10^{-9} m = 10^{-6} mm = 10^{-3} μm.

From Hurlbut and Klein (1977); Schulze (1989).

A particle size analysis is done after removing soil organic matter, usually by oxidation with hydrogen peroxide or hypobromate solutions. Standard sieves are used to mechanically separate out the very fine sand and larger particles from finer particles. The silt and clay fractions are then determined by measuring the rate of settling of these particles from their suspension in water. After the amounts of different soil particles are determined, a definite textural class name (such as sandy loam or clay loam) can be given to a soil using the diagram given in Figure 3.4. Because the size of mineral particles in a soil is not readily subject to change* by soil management practices, the soil texture (texture class) is an important and permanent characteristic of a soil and gives a general picture of the soil's physical properties such as density, porosity, consistency, water holding capacity, and tilth.

3.4.2. Soil Structure

In nature the soil mineral particles do not exist separately. They are bound to each other by oxides and hydroxides of iron, organic substances excreted by plant roots, root pressures, decomposition products of plant residues, microbial cells and fungal hyphae, and excretory products of microorganisms

* The only way to change soil texture of a field is by adding large amounts of soils of different textures brought in from an external source. Rice growers in Asian countries in the upper regions of an undulating topography bring heavy clayey soil from the lower regions or soil at the bottom of the dried ponds and add and incorporate it in the soil of their field to improve texture. Also, flooding or wind erosion sometimes deposits materials of a different texture on the soil surface.

Table 3.3 Classification of Soil Mineral Particles According to Size

Soil separate	International Society of Soil Science (mm)	U.S. Department of Agriculture (mm)
Gravel	2.0 or more	2.0 or more
Sand		
Very coarse		2.0–1.0
Coarse	2.0–0.2	1.0–0.5
Medium		0.5–0.25
Fine	0.2–0.02	0.25–0.1
Very fine		0.1–0.05
Silt	0.02–0.002	0.05–0.002
Clay	0.002 or less	0.002 or less

From USDA (1951).

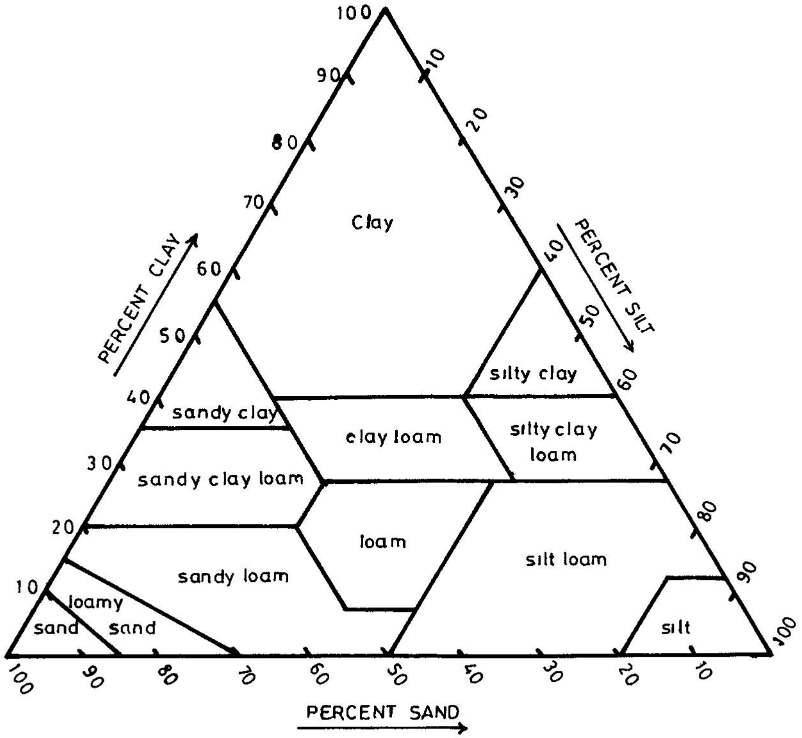


Figure 3.4. Chart showing the percentages of clay (below 0.002 mm), silt (0.002 to 0.05 mm), and sand (0.05 to 2.0 mm) in the basic soil textural classes. (From USDA, 1951.)

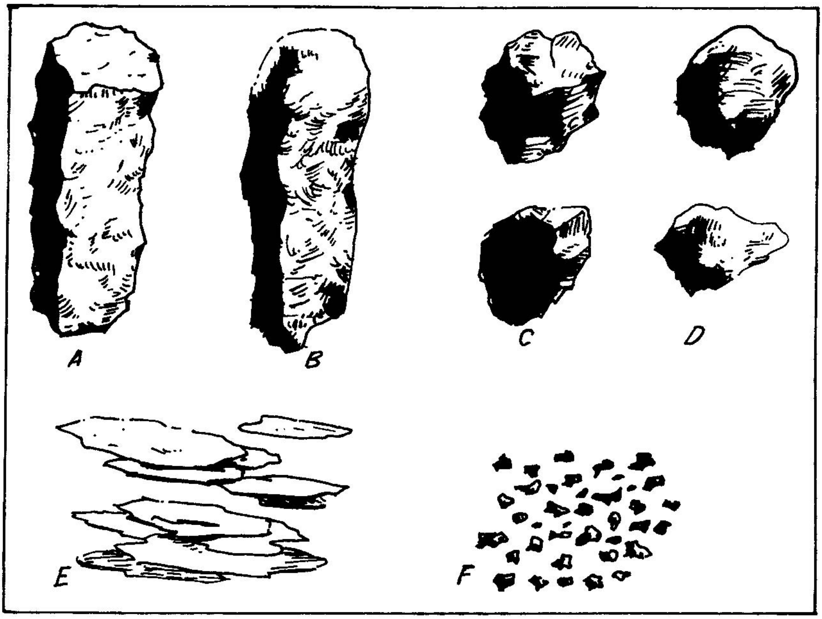


Figure 3.5. Drawings illustrating some of the types of soil structure: *A*, prismatic; *B*, columnar; *C*, angular blocky; *D*, subangular blocky; *E*, platy; and *F*, granular. (From USDA, 1951.)

and gelatinous substances secreted by earthworms. These are aggregated into larger units (or peds) of different sizes and shapes that determine the soil structure. In general, the following four kinds of structures (Figure 3.5) are found in the soils.

Platy. Aggregates are arranged in thin horizontal plates (E in Fig. 3.5). Such structure is found in soils rich in 2:1 layer silicates such as black, cotton soils in India.

Columnar or prismatic. Aggregates are vertically oriented in pillar-like structures, which vary in diameter from a few to as much as 15 cm or more. When the tops of the prisms are rounded, the structure is said to be columnar (B in Fig. 3.5); however, when the tops are plane and level it is said to be prismatic (A in Fig. 3.5). Such structures are found in the subsurface soils of arid and semiarid regions, and in soil derived from wind-blown loess.

Blocky. The aggregates are blocky in shape, more or less equal in three dimensions; one side may be 1 to 10 cm in thickness (C and D in Figure 3.5).

Table 3.4 Relationship Between Land Use Pattern, Organic Carbon, and Water-Stable Aggregates (0.25 mm or More Diameter)

Land use	Soil depth (cm)	Organic carbon (%)	Water stable aggregates (% by wt of soil)
Bare soil	0–15	0.21	11.7
	15–30	0.17	6.6
Corn (after 5-yr cultivation)	0–15	0.30	19.3
	15–30	0.22	1.6
Corn and black gram	0–15	0.34	28.2
(after 5-yr cultivation)	15–30	0.29	15.7
Afforestation (*Ecualyptus tereticornis*:	0–15	0.58	47.0
after 2-yr plantation)	15–30	0.56	57.4
Grassland (*Cenchrus ciliaris*:	0–15	0.61	50.7
after 12 yr of growing)	15–30	0.59	42.2

From Bhatia and Srivastava. 1984. J. Indian Soc. Soil Sci. 32:201–204. With permission.

Granular or crumb. Aggregates are round in shape (F in Figure 3.5). When aggregates are nonporous, the structure is said to be granular, while the porous aggregates (found in organic matter–rich surface soil) give crumb structure. For most crops crumb structure is highly desirable.

While the texture of a soil cannot be easily changed by soil management practices, structure can certainly be altered. An example of this is the destruction of good soil structure by flooding and puddling the soil as practiced in rice cultivation. Thus soil structure (as judged by stable aggregates) can be modified by the land use pattern (Table 3.4). Compaction, such as occurs when heavy machinery is used on wet soils, also destroys soil aggregates.

3.5. SOIL COLLOIDS

A description of soil composition will not be complete without a mention of soil colloids. Finer mineral and organic matter particles form soil colloids.

The word colloid was coined by Graham (1861) from the Greek "κωλλα," which means glue or gluelike materials. A suspension of clay particles or fine organic matter particles would look very much like glue. As a matter fact any substance can acquire colloidal properties if it is broken down to a very fine size; the generally agreed value is 1 μ (micron) (10^{-4} cm or 10^{-3} mm). This size of particle cannot be seen under light microscope, but can be seen under an electron microscope. Still finer size will lead to atomic or molecular stage.

The most important and unique property acquired by a substance when it is broken down to very fine particle size is a many-fold increase in surface area, which is responsible for the great adsorption capacity of colloids.

Table 3.5 Examples of Colloidal Systems

Dispersed phase	Dispersion medium	Colloidal systems
Liquid	Gas	Fog, liquid sprays
Solid	Gas	Smoke, dust
Liquid	Liquid	Milk
Solid	Liquid	Gold sol
Solid	Solid	Colored glass

From Shaw (1968).

The enormous increase in surface area can be visualized when a cube of 1 cm per side (surface area 6 cm^2) is divided into cubes of 1 μ (10^{-4} cm) per side. The surface area of these cubes will be 6×10^4 cm^2. Thus just by reducing the particle size the surface area has been increased 10,000 fold.

Another point that needs to be known about colloids is that colloids are not a substance but a system. Each colloidal system has two components, namely, a dispersed phase (the substance making up the particles) and a dispersion medium. In the case of soil colloids, the clay mineral particles, hydroxides of Al and Fe, and the fine organic matter particles are the dispersed phase and soil water is the dispersion medium. This is an example of solid-liquid colloidal systems. Some other examples of colloidal systems are given in Table 3.5. Colloidal systems where the dispersed phase has an affinity for the dispersion medium are known as lyophyllic (hydrophyllic when water is the dispersion medium), while those where the dispersed phase does not have an affinity for the dispersion medium are known as lyophobic (hydrophobic when water is the dispersion medium). The soil colloidal system is an example of a hydrophillic colloid, while gold sol is an example of hydrophobic colloid. Several properties of the clay minerals, soil organic matter, and hydroxides of iron and aluminum discussed in later chapters are due to their colloidal nature.

3.6. SOIL LIVING ORGANISMS

An examination of a sample of fresh garden soil first with the naked eye and then under a magnifying glass will show it is teeming with different kinds of organisms, which would include earthworms, ants, spiders, mites, and others (Tables 3.6 and 3.7). Microscopic examinations would reveal the presence of nematodes, protozoa, fungi, algae, actinomycetes, and bacteria of thousands of species. A teaspoon of soil may contain as many as a billion organisms. These macro- and microorganisms are responsible for the decomposition of freshly added organic matter and several biological processes of immense importance in soil fertility management. Agricultural management practices greatly influence the number and species of various soil macro- and micro-organisms present. Soil biology is an interesting area of soil research (Burges and Raw, 1967) and has yielded considerable information that is used in soil

Table 3.6 Frequently Occurring Groups of Soil Organisms

Animals (fauna)

I. Macro
  Herbivores and Detritivores
    Mice, squirrels, gophers, shrews, woodchucks
    Ants, beetles, grubs, etc.
    Millipeds, sowbugs, slugs, and snails
    Earthworms
  Largely predators
    Moles
    Insects (ants, beetles, etc.)
    Centipedes
    Spiders
II. Micro
  Protozoa
  Nematodes

Plants (flora)

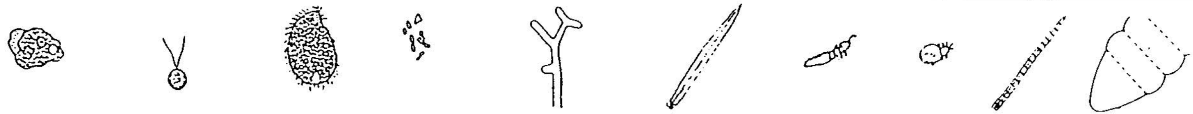
I. Algae: green, blue-green, diatoms
II. Fungi: mushroom fungi, yeasts, molds, VAM mycorrhizae
III. Actinomycetes
IV. Bacteria: aerobic, anaerobic, autotrophic, heterotrophic

Adapted from Brady (1990).

fertility management. Essentially all soil nitrogen that becomes available for crop utilization must first undergo various microbiological transformations. This also holds true for organic P and S sources.

Cultivation practices can considerably influence the population of soil organisms. For example, House and Parmele (1985) from Athens, Georgia, reported 2202 and 637 earthworms m^{-2} in no-till and conventionally tilled plots under a sorghum-rye cropping system. Ground beetles, spiders, and other macroarthropods, as well as microarthropods, were also frequently more prevalent under no-till than under conventional tillage. The no-till method enhances growth of soil organisms because of reduced water loss (more optimum soil water content), amelioration of temperature extremes and fluctuations, and the presence of a relatively continuous substrate for decomposers.

Table 3.7 Average Standing Crop and Energetic Parameters for Microorganisms, Mesofauna, and Earthworms in a Lucerne Ley and Georgia No-Tillage Agroecosystem

	Naked amoebas	Flagellates	Ciliates	Bacteria	Fungi	Microbivorous nematodes	Collembola	Mites	Enchytraeids	Earthworms
										
Typical size in soil	30 µm	10 µm	80 µm	0.5–1 × 1–2 µm	Ø 2.5 µm 1.0–5.5 µm	Ø ~ 40 µm	Ø 5000µm	Ø 1000µm	Ø 1000µm	Ø 5000 µm
Mode of living	In water films on surfaces	Free-swimming in water films		On surfaces	Free and on surfaces	In water films free and on surfaces	Free	Free	Free	Free in soil
Biomass (kg DW/ha)	95%	5%	<1%	500–750[b]	700–2700[c]	1.5–4[d]	0.2–0.5[d]	2–8[d]	1–8[d]	25–50[d]
		50[a]								
% active	0–100			15–30	2–10	0–100	80–100	80–100	?	0–100
Estimated turnover times/season		10		2–3	0.75	2–4	2–3	2–3	?	3
No. of bacteria/division × 10^{-3}	3–8	0.6–1	20–2000							
Minimum generation time in soil (hr)		2–4		0.5	4–8	120	720	720	170	720

Note: DW, dry weight; *0*, diameter
[a]MPN technique.
[b]Direct counts plus size-class estimations.
[c]Direct estimation of total hyphal length and diameter.
[d]Extractions and sorting.
From Coleman et al. (1993).

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